Recent evolution and challenges for oceanic dynamical cores across all scales

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Ocean Modeling for Predictions Workshop

How to improve models for increased prediction skills

Recent evolution and challenges for oceanic dynamical cores across all scales

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Context: oceanic dynamical cores

Acronym	Primary application	Horiz. grid	Method	Vert. coord.	NH option
Croco	coastal	structured	FD/FV	QE	Yes
FESOM	global	unstructured	FV	QE	
GETM	coastal	structured	FD/FV	ALE	Yes
Hycom	global	structured	FD	Lagr. remap	
ICON-O	global	unstructured	FE	QE	
MITgcm	global	structured	FD/FV	QE	Yes
MOM6	global	structured	FD/FV	Lagr. remap	
MPAS-O	global	unstructured	FV	QE/ALE	
NEMO	global	structured	FD/FV	QE/ALE	
Roms-Rutgers	coastal	structured	FD/FV	QE	
SCHISM	coastal	unstructured	FE	QE	
Suntans	coastal	unstructured	FE	Lagr. remap	Yes
Symphonie	coastal	structured	FD	QE	Yes
Thetis	coastal	unstructured	FE	QE	

QE: quasi-Eulerian; ALE: Arbitrary Lagrangian Eulerian;FE: Finite Element; FV: Finite Volume

+ ROMS-Ucla, POM, Mars3d, FVCOM, Delft3d, Mike 3, COCO

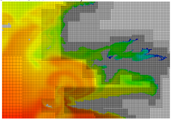
Some Challenges and prospects

- Inclusion of **non-hydrostatic effects**
- **Multi-resolution strategies** (+ local adaptation of model equations)
- ALE/Lagrangian remap **vertical coordinates**
- **(Time/energy/cost)-to-solution** (Green IT) (Time-integration strategies; effective resolution)
- Control of **non-negativity** and dry states
- **Energy consistency** and resolved/unresolved scales coupling
- Control of **spurious modes** and **spectral gaps** (FE methods)

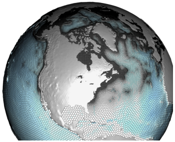
+ Reduce subjectivity and improve reproducibility

Multi-resolution strategies

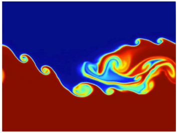
Block structured mesh refinement (Croco Ocean model)



Variable resolution unstructured meshes (Courtesy of D. Engwirda)



Inclusion of NH effects



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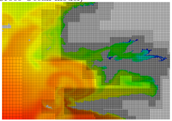

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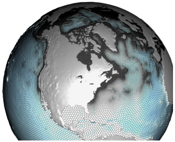
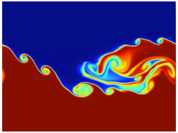


Inclusion of NH effects



Outline

1. (Time/energy/cost)-to-solution

2. Inclusion of non-hydrostatic effects

3. Multi-resolution strategies (+ local adaptation of model equations)

4. Ongoing initiatives

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(Time/energy/cost)-to-solution

(Time/energy/cost)-to-solution

Main drivers:

- Time-integration strategy (stability)
  $\rightarrow$ Eulerian vs (Semi)-Lagrangian time integration
- Effective resolution (accuracy)
  $\rightarrow$ Dissipative and dispersive properties of numerical schemes
- Software environment (efficiency)
  $\rightarrow$ Local vs global communications
  $\rightarrow$ Memory/IO access pattern

Hardware evolution: many-core architectures and co-processors (GPUs)

$\rightarrow$ Methods with local stencils (e.g. Eulerian-based time integration approaches) will be favored [**Mengaldo et al., 2019**]

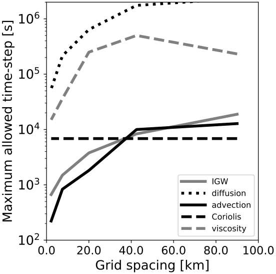
Stability of time-integration

▷ **Limiting process at high resolution**: advection (especially vertical adv.)

- Semi-Lagrangian approach not competitive in the oceanic context (e.g. **[Subich et al., 2020]**)
- Efficiency of Eulerian-based time integration for advection (with 3rd-order spatial discretization)

Scheme	LFRA	LFAM3	AB3	RK3	DST
Efficiency	0.47	0.44	0.397	0.54	1

efficiency = (Max time-step) / (number of rhs computation)



[Lemarié et al. (2015)]

▷ Active research within the **H2020 IMMERSE project** to define the most efficient time-integration procedure (RK3 is the frontrunner so far)

▷ An unconditionally vertical advection scheme in NEMO allowed to increase the **time-step of ORCA025 from** $\Delta t = 1200$ s **to** $\Delta t = 1800$ s for a marginal increase of the computational cost per time-step.

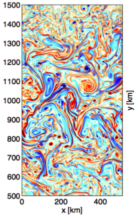
Computational aspects

Sequential performance (Intel Vtune profiler)

	NEMO (3.6)	CROCO (ROMS)	Mars3D
Memory size	2Gb	800Mb	1,4Gb
Number of instructions	5.5 bil.	3.3 bil.	**13.9 bil.**
Vectorization (%)	40	**78**	45
Cache bound[1] (%)	14	14	**71**
FP Arith./Mem. Rd Instr.[2]	0.56	**1.43**	0.62
Execution time (s)	**609**	**160**	**686**

[1] percentage of execution time spent in cache memory accesses

[2] floating point arithmetic instructions per Memory Read or Write



Baroclinic jet testcase
[**Soufflet et al., 2016**]

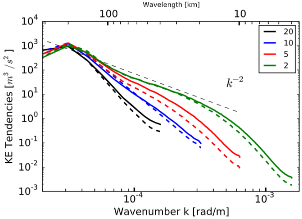


Fig. 12. Near surface KE spectra (m^3/s^2) for ROMS (solid lines) and NEMO (dashed lines) at 20 km, 10 km, 5 km and 2 km resolution.

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Inclusion of non-hydrostatic effects

Example (strait of Gibraltar)

$$r = \frac{\text{NH pressure}}{\text{Hydro pressure}} = \frac{\varepsilon^2 U_0^2 \text{Ro}}{\max\left(U_0^2, H_0^2 N_0^2\right)}$$

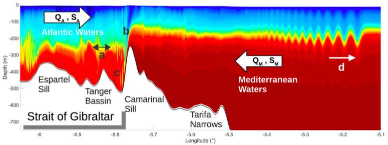
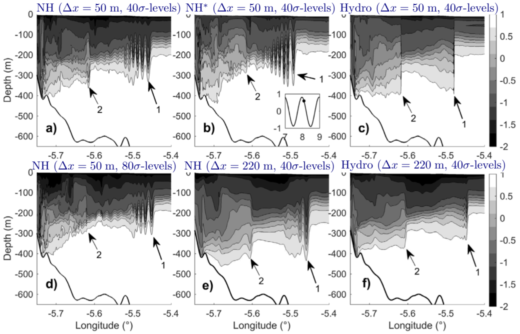


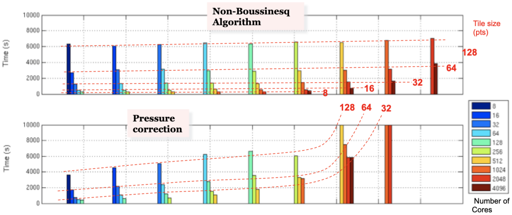
Fig. 1. Illustration of small-scale processes in the Strait of Gibraltar induced by tidal interaction with stratification and bathymetry. (a) Linear/Small amplitude internal wave. (b) Hydraulic Jump. (c) Kelvin–Helmholtz instabilities. (d) Large-amplitude internal waves or internal solitary waves (ISW).



[Hilt et al., 2020]

Solution methods

- **Incompressible pressure projection/correction approach** (MITGcM, Suntans, Croco-NH, FVCOM, etc.)
  - $\rightarrow$ Global 3D elliptic Poisson equation
  - $\rightarrow$ Overhead of about 150% vs hydrostatic is generally reported
  - $\rightarrow$ Overhead depends on solver, tolerance, geometry, etc
- **Pseudo-compressible approach** [**Auclair et al., 2018; Hilt et al., 2020**] (Croco, SNH)
  - $\rightarrow$ Local problem with explicit treatment of acoustic mode (good scaling)



- **Artificial compressibility method** [**Lee et al., 2006; Marsaleix et al., 2019**]
  - $\rightarrow$ Global 3D parabolic problem and inaccurate continuity equation (Symphonie)
- **Diagnostic approach for NH pressure** [**Klingbeil & Burchard, 2013**]
  - $\rightarrow$ Not robust enough for practical use (GETM)

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Multi-resolution strategies (+ local adaptation of model equations)

Multi-resolution strategy (static refinement)

- **Strategy#1**: multiresolution simulations using **block structured mesh refinement** **[Debreu & Blayo, 2008; Debreu et al., 2012]**
- **Strategy#2**: **variable resolution unstructured mesh** **[Sein et al., 2016,2017; Hoch et al., 2020]**

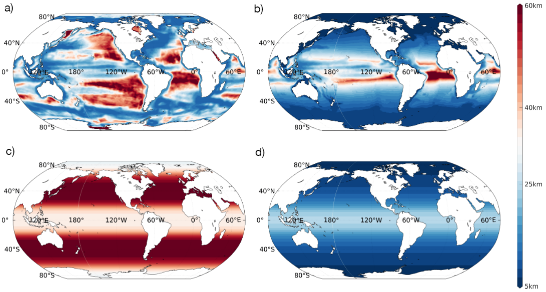
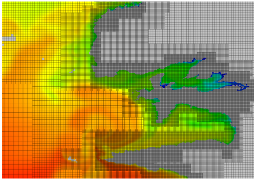


Figure 3. Resolution maps for various unstructured model configurations, showing (clockwise, from top-left): (a) the FESOM HR mesh, with resolution adapted to a measure of SSH variability, (b) the FESOM XR mesh, with resolution scaled to estimates of one-half of the Rossby radius, (c) the MPAS-O high-resolution RS-18-to-6km eddy-permitting mesh, and (d) the MPAS-O low-resolution EC-60-to-30km eddy-paramerterised mesh.

4 levels of refinement from 350 m to 2.8 km (Croco)



- Level 1: 100% (1 grid)
- Level 2: 43% (8 grids)
- Level 3: 18% (20 grids)
- Level 4: 7% (46 grids)

Multi-resolution strategy (static refinement)

- **Strategy#1**: multiresolution simulations using **block structured mesh refinement** [**Debreu & Blayo, 2008; Debreu et al., 2012**]
  → *ongoing CMEMS project to generalize this approach to NEMO*
- **Strategy#2**: **variable resolution unstructured mesh** [**Sein et al., 2016,2017**] in FESOM, [**Hoch et al., 2020**] in MPAS-O

Possible alternatives:

▷ An unstructured grid model like FESOM offers the flexibility to be structured in the middle of the basin (with quadrangles) and unstructured at the coast (with triangles).

▷ Offline nesting (comes with a lot of subtleties and tuning in OBC treatment + possibly large phase difference between the coarse- and nested-grid solutions).

Strategy#1: block structured mesh refinement

- + Time-step locally adapted to spatial resolution
- + Parameter values and numerical schemes adapted for each level of refinement
- + Built upon mature numerical methods and computational library (e.g. Agrif)
- + Conservation properties and consistent phase between the coarse- and nested-grid solutions at the nested-grid boundary (unlike in offline nesting)
- - Coarse and fine resolution grids need to share common edges
- - Time-stepping rather complex for coupling at the barotropic time-step level
- - Data processing for a large number of grids

Strategy#2: variable resolution unstructured meshes

- + Smooth transition of mesh resolution to minimize numerical artefacts
- + Flexibility in the mesh definition to adjust to very complex geometries
- - Time-step for explicit methods set by the finer resolution
- - Scale-aware parameterizations
- - Mesh generation
- - Data processing (loss of information when not using the native grid)

Multi-resolution with local adaptation of model equations

- **Strategy#1**: use block structured mesh refinement with high-resolution NH nests into a coarse resolution primitive equations model.

  $\rightarrow$ *PhD of E. Duval funded by French navy (Croco)*

- **Strategy#2**: use variable resolution unstructured meshes with automatic selection of NH zones [**Voltzinger & Androsov, 2016**]

  $\rightarrow$ *detection of zones where NH solution is needed*

$$r = \frac{\text{NH pressure}}{\text{Hydro pressure}} = \frac{\varepsilon^2 U_0^2 \mathrm{Ro}}{\max\left(U_0^2, H_0^2 N_0^2\right)}$$

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Ongoing initiatives

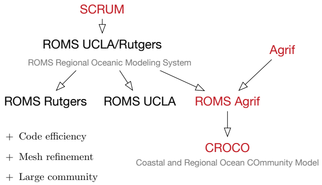
French context: the CROCO initiative

Phase 1: COMODO project (2012-2016, PI: L. Debreu, Inria)

- Most modeling groups had common objectives for coastal applications (e.g. NH option, flexible horiz. and vert. grids, coupling with waves, etc)
  - Minimize the duplication of efforts
  - Promote **interoperability across numerical models** (e.g. Oasis, XIOS)

Phase 2: CROCO Research group (supported by Ifremer, SHOM, Cnrs, Ird, Inria)

▷ Roms-Agrif numerical kernel
▷ Online nesting capability via Agrif library
▷ Non-hydrostatic Non-Boussinesq from S-NH
▷ Sediment module from Mars3d
▷ OAW coupling interface (shared w. Nemo)
▷ ALE-type vertical coordinate (ongoing + shared w. Nemo)



Complementary to NEMO in term of target applications

International context: the COMODORE initiative

Motivation : *”bring together a community of “model oriented” researchers to foster regular exchanges and share expertise on outstanding issues and perspectives, irrespective of target applications (regional, coastal, or global)”* [**Lemarié et al., 2019**]

Actions :

- Collective paper *”Challenges and prospects for dynamical cores of oceanic models across all scales”* In preparation for JAMES
- Special issue on oceanic dynamical cores and their evaluation to come in JAMES
- Test strategy and benchmark suite
  - define evaluation methods to compare the behavior and performances of different models
  - existing test cases are scattered in the literature and not always fully documented and reproducible
  - motivate communication between modeling groups and open room for prospective approaches from applied mathematicians

Models represented: Croco, FESOM, GETM, Hycom, ICON, MITGcM,MOM6,MPAS,NEMO,ROMS, SCHISM, Suntans, Symphonie, Thetis.

Recent references

- Auclair, F., Bordois, L., Dossmann, Y., Duhaut, T., Paci, A., Ulses, C., & Nguyen, C. (2018). **A non-hydrostatic non-boussinesq algorithm for free-surface ocean modelling**. Ocean Modell.
- Fox-Kemper, B., Adcroft, A., Boning, C. W., Chassignet, E. P., Curchitser, E., Danabasoglu, G., . . . Yeager, S. G. (2019). **Challenges and prospects in ocean circulation models**. Front. Mar. Sci.
- Fringer, O. B., Dawson, C. N., He, R., Ralston, D. K., & Zhang, Y. J. (2019). **The future of coastal and estuarine modeling: Findings from a workshop**. Ocean. Modell.
- Griffies, S.M., Adcroft, A. & Hallberg, R. (2020). **A primer on the vertical Lagrangian-remap method in ocean models based on finite volume generalized vertical coordinates**. To appear in JAMES
- Klingbeil, K., Lemarié, F., Debreu, L., & Burchard, H. (2018). **The numerics of hydrostatic structured-grid coastal ocean models: State of the art and future perspectives**. Ocean Modell.
- Lemarié, F., Burchard, H., Debreu, L., Klingbeil, K., & Sainte-Marie, J. (2019). **Advancing dynamical cores of oceanic models across all scales**. Bull. Am. Meteorol. Soc.
- Lemarié, F., and Commodore group (2020). **Challenges and prospects for dynamical cores of oceanic models across all scales**. In prep. for JAMES